Kinetic modeling of the H atoms in the heliospheric interface: solar cycle effects

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Abstract. In this paper we present results of a new time-dependent kinetic model of the H atom penetration through the solar wind - interstellar medium interaction region. The kinetic 6D (time, two dimensions in space, and three dimensions in velocity-space) equation for interstellar H atoms was solved self-consistently with time-dependent Euler equations for the solar wind and interstellar charged components. We study the response of the interaction region to the 11 year solar cycle variations of the solar wind. The termination shock location varies within ± 7 AU, the heliopause variation is ~ 2 AU, and the bow shock variation is negligible. At large heliocentric distances, the solar cycle induces 10-12 % of fluctuations in the number density of both primary and secondary interstellar H atoms and atoms created in the inner heliosheath. Closer to the Sun the variation increases up to 30-35 % at 5 AU due to the solar cycle variation of the charge exchange rate. Solar cycle variations of interstellar H atoms in the heliospheric interface and within the heliosphere may have a major importance for the interpretation of H atom observations inside the heliosphere.

INTRODUCTION

More than 30 years (three solar cycles) observations of the solar wind show that its momentum flux varies by factor of ~ 2 from solar maximum to solar minimum. It was shown theoretically that such variations of the solar wind momentum flux strongly influence the structure of the heliospheric interface - the region of the solar wind interaction with the local interstellar medium. Most of global models studying the solar cycle effects ignored the interstellar H atom component or took this component into account by using simplified fluid or multi-fluid approximations (e.g. Baranov and Zaitsev 1998; Zank and Mueller, 2003; Scherer and Fahr, 2003). These simplifications were done because it is difficult to solve a 6D (time, two dimensions in space, and three dimensions in velocity-space) kinetic equation for the interstellar H atom component. Kinetic description of interstellar atoms is necessary due to their large mean free path comparable with the size of the heliospheric interface. Recently, it has been shown explicitly by Izmodenov et al. (2001) that the velocity distribution function of interstellar atoms is not Maxwellian. Fluid and multi-fluid approaches for the interstellar H atoms are not valid and may result in incorrect solutions and incorrect interpretations of observational data. At the same time, the momentum flux variations of the solar wind may have a significant effect on the distribution of interstellar H atoms in the heliosphere due to coupling of the atom and plasma components by charge exchange. In this paper we summarize first results of our self-consistent model of the heliospheric interface, which takes into account solar

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cycle effects. The main advantage of our model as compared with previously published multi-fluid models is a rigorous kinetic description of the interstellar H atoms.

The structure of the heliospheric interface is as follows. The solar wind plasma decelerates and turns to the tail at the termination shock (TS), while the interstellar plasma decelerates and turns away from the axis of symmetry in the bow shock (BS). The heliopause (HP), which is contact discontinuity, separates these two plasma flows. Hydrogen atoms newly created by charge exchange have the velocities of their proton partners in the charge exchange collisions. Therefore, the properties of these new atoms depend on the local plasma properties. It is convenient to distinguish four different populations of H atoms: 1) atoms created in the supersonic solar wind, 2) atoms originating in the heliosheath and known as heliospheric ENAs (Gruntman et al., 2001), 3) atoms created in the disturbed interstellar wind, 4) original (or primary) interstellar atoms.

MODEL

In this work we advance the heliospheric interface model developed by the Moscow group (e.g. Baranov and Malama, 1993; Izmodenov et al., 2003a,b) by introducing 11 year sinusoidal variations of the solar wind in the model. A detailed description of the model including governing equations and method of their solution are given in Izmodenov et al. (2004). Our method allows to get a solution of the system of Euler equations self-consistently with 6D kinetic equation and fulfill the periodic boundary conditions. We have studied the effects of the solar cycle variations of the solar wind dynamic pressure by varying sinusoidally the solar wind density by a factor of 2: $n_{p,E} = n_{p,E,0}[1+\delta_n \sin(2\pi t/T)]$, where $\delta_n = 1/3$, T= 11 years. As it was pointed out by Zank and Mueller (2003) the solar cycle effects in the heliospheric interface do not care whether the variations in the solar wind dynamic pressure are caused by the solar wind velocity or density variations. Boundary conditions in our calculations were chosen as following: $n_{p,E,0}$ = 8.0146 cm^{-3}, $n_{He^{++},E,0}$ = 0.26 cm^{-3}, $V_{sw,E}$= 445.136 km/s, where $n_{p,E}$, $n_{He^{++},E}$, $V_{sw,E}$ are solar proton and alpha particles number densities and the solar wind velocity, respectively. The ratio of $n_{He^{++},E}/n_{p,E}$ was assumed to be constant. The bulk velocity, temperature, number density of H atoms, protons, and helium ions in the undisturbed LIC were chosen as following: V_{LIC} = 26.4 km/s, T$_{LIC}$ = 6500 K, $n_{H,LIC}$ = 0.18 cm^{-3}, $n_{p,LIC}$ = 0.06 cm^{-3}, $n_{He^{+},LIC}$ = 0.009 cm^{-3}.

RESULTS: PLASMA

The discontinuities vary with a 11-year time-period under action of the 11-year fluctuation of the solar wind dynamic pressure at the inner boundary of our computational grid. The termination shock varies around its stationary distance, 100 AU, from its minimal distance of $\sim$93 AU to its maximal distance of $\sim$107 AU. Fluctuations of the TS become larger toward the downwind direction as compared to upwind. The variation of the TS in the downwind direction is $\sim$25 AU from its minimal value of $\sim$163 AU to its maximal value of $\sim$188 AU. In the upwind direction the most distant position of the termination

TABLE 1. Comparison of our results with results of multi-fluid model by Zank and Mueller (2003)

Model	Δ TS (upwind)*	Δ TS (downwind)	Δ HP (upwind)
Zank and Mueller (2003)	7 AU	50 AU	6 AU
This paper	14 AU	25 AU	4 AU

* $\Delta = R_{max} - R_{min}$ is the difference between maximal and minimal heliocentric distances to the TS and HP during the solar cycle.

shock is reached ∼1.5-year after the maximum of the solar wind dynamic pressure at 1 AU. The phase of downwind fluctuations of the TS is shifted by ∼3.5 years as compared with the phase of the upwind fluctuations. It is interesting to compare our results with the results obtained by Zank and Mueller (2003) on the basis of multi-fluid descriptions of the interstellar H atoms (Table 1). Although the boundary conditions in the two papers are not equivalent, the comparison shows the qualitative differences of the results. For example, the variations of the TS is two times larger in our model in the upwind direction and two-times smaller in the downwind direction.

The strength of the TS has important consequences for the spectra of anomalous cosmic rays (ACRs), because the velocity jump at the TS relates to the spectral index of ACRs β, which determines the variation of intensity of the cosmic rays j with energy E: $j \sim E^{\beta}$. We have computed the variation of the velocity jump at the TS. In the upwind direction the jump of the plasma velocity at the TS, or, in other words, the strength of the TS, varies from its minimal value of 2.92 to its maximal value of 3.09. This corresponds to a variation of β from 1.28 to 1.22. The strength of the TS varies from 2.92 to 3.17 in the downwind direction. This strength variation translates into the variation of β from 1.28 to 1.19.

The heliopause fluctuates with smaller amplitude as compared to the termination shock. It varies from 169 AU to 173 AU in the upwind direction. The upwind distance to the heliopause averaged over the solar cycle is 171 AU. This coincides with the stationary solution. The solar-cycle induced fluctuation of the BS is less than 0.1 AU in the upwind direction. The distance to the BS averaged over the solar cycle is ∼308 AU, while this distance is 311 AU in the case of the stationary solution.

Plasma number density performs 11-year fluctuations in the entire computation region (Figure 1, left column). However, the wave-length of the plasma fluctuations in the solar wind is apparently larger than the distances to the TS and HP. It means time snap-shots of distributions of plasma density, velocity and temperature are not qualitatively different from a stationary solution. The situation is different in the outer heliosheath, the region between the HP and BS. The 11-year periodic motion of the heliopause produces a number of additional weak shocks and rarefaction waves (Baranov and Zaitsev, 1998; Zank and Mueller, 2003). The amplitudes of these shocks and rarefaction waves decrease while they propagate away from the Sun due to increase of their surface areas and interaction between the shocks and rarefaction waves. To resolve the wave structure we increased the spatial resolution of our computational grid in this region in three times. We have checked also that additional increase of the spatial and time resolution of our computational grid in the entire computational domain does not change the results. The characteristic wavelength of the plasma fluctuations is $\sim$40 AU in the region between the BS and HP. Long-scale waves were also obtained in plasma distributions in the post-shocked plasma of the downwind region. Amplitudes of the waves are much less than in the upwind direction and the wavelength is $\sim$200 AU.

A comparison of the distributions of the interstellar plasma distributions averaged over 11 years with those obtained from solution of the stationary problem with exactly the same inner and outer boundary conditions as in the time-dependent model, shows the two distributions practically coincided. Note, that our results contradict the conclusion made by Zank and Mueller (2003) that "the shocks provide additional heating in the heliotail and outer heliosheath". According to our calculations the shock-waves are weak and the heating is so small, that it is not noticeable in distributions of plasma temperature.

RESULTS: H ATOMS

Charge exchange significantly disturbs the interstellar atom flow penetrating the heliospheric interface. Atoms newly created by charge exchange have velocities of their ion partners in the charge exchange collisions. Therefore, the velocity distribution of these new atoms depends on the local plasma properties in the place of their origin. As it was specified in the introduction, it is convenient to distinguish four different populations of H atoms depending on the region in the heliospheric interface where the atoms were created.

Figure 1 presents time-variations of number densities, bulk velocities and kinetic temperatures of three populations of H atoms at different heliocentric distances in the upwind direction. All moments of the distribution function are normalized to their initial values at $t = 0$. Clear 11-year periodicity is seen for the number densities of the atoms. Deviations from exact 11-year periodicity are connected with errors of our statistical calculations, which are $\sim$2-3 %. Less than 10 % variation (from maximum to minimum) is seen for number densities of all populations at distances larger than 10 AU. At 5 AU the variations are of the order of 30 %. Variations of the bulk velocity and kinetic temperature are negligibly small for both primary and secondary interstellar populations. However, the bulk velocity and kinetic temperature of atoms created in the inner heliosheath vary with the solar cycle on 10-12% level. This is connected with the fact that most of the H atoms of the latter population are created in vicinity of the heliopause and they reflect long wavelength plasma variations in this region.

It is important to note, that the number densities of all three components of H atoms fluctuate in the same phase. Such coherent behavior of fluctuations remains in all supersonic solar wind region ($R <$90 AU) for the three populations of H atoms, and in the inner heliosheath for the primary and secondary atoms. The reason of such coherent behavior of the variations of the H atom densities becomes evident when we compare them with the variations of plasma density (Figure 1, left column). The two quantities vary almost in anti-phase. Apparently, such a correlation is only possible when temporal variations of the H atom densities are caused by variation of the local loss of the neutrals due to the charge exchange and ionization processes. The local fluctuations are not transported over large distances because of chaotic velocities of individual atoms and

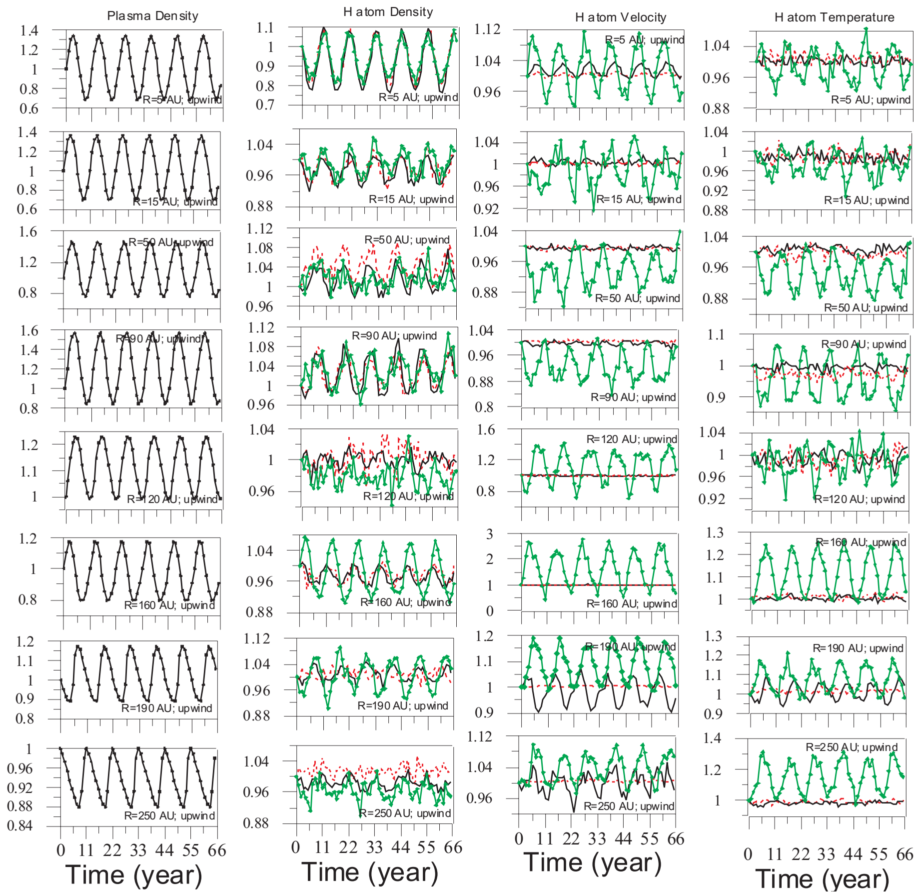

FIGURE 1. Number densities (second column from left), bulk velocities (second column from right) and kinetic temperatures (right column) of primary (solid curves) and secondary (dashed curves) interstellar atom populations and atoms created inner heliosheath (curves with diamonds) at different heliocentric distances in the upwind direction as functions of time. For comparison, the number density of plasma is shown (left column). All moments of the distribution function are normalized to their values at t=0.

their large mean free path.

However, coherent fluctuations of different populations of H atoms disappear in the regions where the populations originate, and process of creation is dominant as compared with the losses. Indeed, in the inner heliosheath (for example, at 160 AU in upwind as shown in Figure 1) fluctuations of the number density of H atoms created in this region are shifted as compared with coherent fluctuations of primary and secondary interstellar atom populations and are in phase with variations of proton number density near the heliopause. Variations of the secondary interstellar atom populations are in anti-phase with variations of primaries in the outer heliosheath (see, R=190 AU in Figure 1) and almost in phase with plasma fluctuations in the region. Again, the creation processes is dominant in the outer heliosheath for the population of the secondary interstellar atoms.

Our calculations show (Izmodenov et al., 2004) that as for the plasma component there is no any noticeable difference between time-averaged distributions of H atoms and the solution of stationary problem. Finally, it is important to note, that behavior of H atom populations in the heliospheric interface described above has a kinetic nature. The validity of fluid approach to be used is determined by simple general criteria, that Knudsen number $Kn = l/L \ll 1$, where l and L are the mean free path of the particles and characteristic size of the problem, respectively. For the stationary problem the distance between the HP and BS, which is approximately 100 AU, can be chosen as characteristic size of the problem. The mean free path of H atoms in the region is ~ 50 AU. Therefore, $Kn_{stationary} \approx 0.5$. The results of kinetic and fluid approaches were compared by Baranov et al. (1998) and Izmodenov et al. (2001) who have shown explicitly that the velocity distribution function of H atoms is not Maxwellian anywhere in the interface. For the time-dependent problem considered in this paper the characteristic size, L, determines as half of the wavelength of plasma fluctuations. In the region between the HP and BS $L \approx 20$ AU. Therefore, $Kn_{time} \approx 2$ and fluid approaches become even less appropriate than for the stationary model. This fundamental reason could be the cause of the large discrepancy between our results and results obtained by Zank and Mueller (2003) and Scherer and Fahr (2003) who used the multi-fluid approaches.

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